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A framework to technically evaluate integration of utility-scale photovoltaic plants to weak power distribution systems

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HIGHLIGHTS

- Presenting a framework to assess connecting PV plants to weak distribution systems.
- Determining required technical analyses to perform when connecting large PV plants.
- Predicting impacts of PV plants at design stage and finding improvement techniques.
- Validating the developed proposal for multiple real-world PV integration projects.

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ABSTRACT

Weak power distribution systems are those that are highly sensitive to fluctuations in voltage magnitude and/or frequency. Due to the intrinsic intermittency and inertia-less nature of photovoltaic systems, the connection of a utility-scale photovoltaic plant to a weak distribution system can lead to grid instability or even collapse. This paper presents a structured framework for performing grid connection studies to evaluate the integration of photovoltaic plants into weak distribution systems. The two main characteristics of weak distribution systems (i.e., low-inertia and high-impedance connection points) are handled separately since each factor has distinct issues, risks and mitigation methods. Also, some systems may only exhibit weakness in one of these aspects, but not the other. Recommendations are provided in the paper for the appropriate studies to be performed and the features to be investigated for the development of utility-scale photovoltaic plants connected to weak distribution systems.

1. Introduction

Large utility-scale photovoltaic plants (referred to as 'PV plants' in the rest of this paper) are inertia-less and intermittent in nature; thus, their output power is subject to weather-induced fluctuations (such as cloud movements) and daylight patterns [1,2]. As a result, the power distribution system to which the PV plant is connected must have enough flexibility to respond to the PV plant's active power variations over short-term intervals [3–5]. Despite these weaknesses, PV plants have a number of advantages that make them attractive to power plant developers, e.g. competitive capital costs, largely modular design that facilitates rapid construction schedules, lower environmental impacts compared to other forms of generation, no ongoing fuel costs and relatively low operations and maintenance requirements [6,7]. In many cases, PV plants are the least cost generation option [8]. Hence, they are currently in the midst of a worldwide development boom and have contributed significantly to the 45-fold increase in the global installed solar power capacity between 2005 and 2015. As solar incentive programs in Europe and North America are wound down, developers are increasingly looking outside these mature markets and beginning to make forays into developing countries [9]. While this includes large markets such as China [10] and India [11], smaller developing markets in Asia, Africa and South America are also being targeted. For remote and isolated areas, PV plants also deliver economic benefits by lowering average energy generation costs [12]. However, the electricity networks in many developing countries are less robust and are less capable of accommodating PV plants when compared to the large interconnected grids of Europe and North America [13].

Grid code and network operator requirements for connecting PV plants are typically generic and written for large interconnected grids. As a result, they may not be suitable for analyzing connections to WDSs, which are more sensitive to frequency and/or voltage fluctuations [14].

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Therefore, special attention needs to be given to address the key issues specific to weak distribution systems (WDS). Power system modeling accuracy is also more crucial in WDSs as the margin for error is lower, and a single bad actor can lead to system-wide issues.

Although [15,16] have reviewed and presented network management techniques for WDSs, the majority of the literature on integrating renewable sources into WDSs such as [17,18] focus on the grid's sensitivity to either frequency and/or voltage, but do not provide any systematic methods or criteria for assessing grid impacts. A comprehensive review of generator connections to WDSs is provided in [14]; however, its discussions are applicable to all types of generators and is primarily a comparison of how different international grid codes relate to WDSs. Refs. [3,18] examine the issues related to grid integration of PV plants from the frequency and voltage stability perspective, but both works are more general in scope and do not explicitly consider WDSs. Refs. [1,4] consider the integration of PV plants from the utility operations perspective and identify the key challenges in frequency and voltage control while highlighting the need for better power system flexibility, but do not give any specific guidance for WDSs.

Ref. [19] provides a comprehensive review of connecting inverter-based resources into voltage-weak grids while [20,21] explore the integration of PV plants into weak radial distribution networks and emphasizes on voltage control and quality issues only. Ref. [22] proposes a method for calculating the maximum penetration limit of PV plants in WDSs, taking into account grid weaknesses in frequency and voltage, but the applied method only considers transient frequency and voltage limits and is more applicable for project screening.

Ref. [23] discusses the importance of inertia in a power system and the operation of future power systems with high penetrations of inertia-less generation. While the paper is not confined to WDSs, it briefly discusses the operational issues encountered in low-inertia systems. Refs. [24,25] present case studies for integrating high penetration of PV plants into two small isolated systems and include analysis of frequency stability and generator dispatch patterns considering minimum machine loading.

Considering the abovementioned points, there is currently no coherent policy or framework for classifying, analyzing and assessing the connection of PV plants to WDSs. Therefore, developing a coherent framework to analyze and evaluate the connection of utility-scale PV plants to WDSs is the research gap that this paper attempts to address. This is very important as grid code and network operator requirements for connecting PV plants are typically generic and developed for large interconnected grids. As a result, they may not be suitable for connections to WDSs, which are more sensitive to frequency and/or voltage fluctuations. As an example, a 5 MWp PV plant that was constructed and connected to a WDS in Nusa Tenggara Timur, Indonesia, had to be curtailed to 2 MWp at the operation stage due to observed grid instability issues that were not identified at the planning phase because of ignoring the differences between the WDS and large interconnected systems [26]. The proposed framework is based on the existing literature, as well as the practical experiences and knowledge gained by the authors in performing grid connection studies for PV plants in WDSs in the Philippines, Indonesia, Bangladesh, and several Pacific island states. A few of the PV plant developments have reached commercial operation such as the 7.48 MWp Tarlac project in the Philippines [27], while others are in various stages of development and some have been abandoned on technical and/or economic grounds, as will be briefly discussed throughout the paper.

The main contributions of this paper to the research field are:

- Developing metrics to identify and classify weak points within the distribution networks of remote areas and islands,
- Determining the required technical analyses to be performed when connecting utility-scale PV plants to such points, and
- Developing a framework to be used by the distribution network operators at the decision-making process for approving PV plant connection to the networks in remote areas and islands and the possible mitigation techniques when technical criteria are not met.

The rest of the paper is organized as follows: Section 2 describes the objectives and requirements of grid connection studies for utility-scale PV plants, and discusses how they fit into the PV plant development process. The criteria for classifying PV plant connection points as either weak (low-inertia and/or high-impedance) or strong are introduced in Section 3 while Section 4 presents the proposed framework for assessing the connection of PV plants to WDSs. This section details the assessment of weak high-impedance connection points and weak low-inertia connection points, as well as the common analyses that are applicable to all connection points. Then, several real study cases in Southeast and South Asia are discussed in Section 5 to elaborate more how the proposed framework has impacted these projects. Finally, the general findings of the paper are summarized in the Section 6.

2. Grid connection studies for PV plants

The grid connection process is often initiated during the feasibility study stage of a PV plant development, where a grid connection application is lodged with the electricity network operator. As part of the application, the network operator requires a grid connection study to be performed. Depending on jurisdiction, the study is either performed by the network operator or it is deemed as contestable work that can be undertaken by third parties.

The overall grid connection study commonly consists of two subsidiary studies: (1) Grid impact study, which assesses the grid's capability to integrate the PV plant without adversely affecting the overall system, and (2) Grid code compliance study, which evaluates whether the PV plant and its equipment are technically compliant to the local rules and requirements (e.g., compatibility with tolerances of voltage and frequency variation, harmonics, flicker, etc.). Therefore, the grid impact study has a wider external focus towards the rest of the network whereas the grid code compliance study is more focused on the capabilities of the PV plant itself.

The grid connection study needs to be reviewed and approved by the network operator before the connection application can be accepted and a connection agreement is signed. An outcome of such a study is the identification of any network augmentations or non-network solutions (such as demand response) that are necessary to connect the PV plant, the costs of which may need to be borne by the network operator, the developer or are shared [28]. Alternatively, the conclusions of this type of study may set an upper limit on the maximum capacity of the PV plant that can be connected without additional network upgrades.

Grid codes and network operator study requirements are typically generic in nature and do not have special provisions for WDSs. It is usually left to the network operator's discretion to decide which studies are appropriate on a case by case basis. This paper argues that a more systematic approach is needed when connecting PV plants to WDSs, with specific issues investigated depending on the strength of the grid connection point.

3. Weak and strong connection points

According to the IEEE Guide for planning dc links terminating at ac locations having low short-circuit capacities (IEEE Std-1204) [29], the strength of a distribution system can be characterized by the system's inertia and network's impedance (i.e., short-circuit capacity). These two factors dictate the sensitivity of the distribution system to fluctuations in frequency and voltage magnitude, respectively. Note that while inertia is a system-wide measure, the network impedance varies throughout the distribution system and is location-specific [30]. Thus, in the context of connecting a PV plant to a network, the concept of a weak connection point is one in which the network impedance at the connection point is high and/or the system inertia is low, both relative